The Long Journey of NWS Medium_Range Prediction

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1. Introduction. This paper's focus is on medium-range [1] forecasting from the late-1970s to present. However, there is much to be gained in perspective by examining, in overview, the very early history of this activity (Section 2). Section 3 discusses the leap from subjective to NWP-based forecasts. Section 4 discusses the current state of 6-10 day and 8-14 day prediction.

Medium-range forecasts are here defined as forecasts of average conditions beyond the range for which individual daily forecasts have useful skill, ending about two weeks to, possibly, 30 days in the future. Today, this includes forecasts of 5-day means of 500 hPa height (Z), surface temperature (T) and total precipitation (P) at a lead of 5 days, in other words, an average of days 6-10 in the future. Similarly, forecasts of 7-day means of 500 hPa height, surface temperature and total precipitation at a lead of 7-days, or, an average of days 8-14 in the future. The term "lead" refers to the number of days between the release of a forecast and the first moment of its valid period. Both 6-10 day and 8-14-day forecasts are given in three categories, whose chance likelihood over 30 years is 33 1/3 % each (terciles). The maps of T and P forecasts (Fig. 1) show the total probability of the occurrence of the indicated category , while maps of the Z forecasts (Fig. 2) are in the form of deterministic heights and anomalies. Month after month, year after year, routine monthly surveys of the number of visitors to CPC's web indicates these two forecasts are the most popular of CPC's many products.

2. The Foundation of Medium Range Prediction. Though the history of prediction dates to the late 19th and early 20th centuries (Appendix 1) the roots of modern medium and long_range forecasting can be traced back to the Dust Bowl of the 1930's, which led to passage in Congress of the Bankhead_Jones Act of 1935, through which MIT was funded to study long-range forecasting. The very first climate forecasts actually distributed to the public by the U.S. Weather Bureau, for an average of days 1-5 in the future, were prepared each Monday and Thursday at MIT, between July, 1940 and April, 1941. Many of those in the MIT group were transferred to the U.S. Weather Bureau and began preparing and disseminating these 1-5 day average forecasts of circulation, temperature and precipitation under the direction of MIT alumnus Jerome Namias (Hughes, 1983). These are the ancestors of modern medium range forecasts.

The basic theory behind these subjectively-produced forecasts was the elegant theory of the motion of the long waves (Rossby et al. 1939). Namias, a Rossby student at MIT, developed methods to predict the mean flow pattern over days 1-5. Namias (1943), describes the essential requirements for making mean 1-5 day forecasts as including: 1) an understanding of the structure, annual cycle and behavior of the general (large-scale) circulation of the atmosphere, 2) an analysis of the observed circulation at the surface and 700 mb and its deviation from its climatology, 3) the formation of troughs and downstream wave trains, as the air particles,

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[1] Medium range forecasts: defined as forecasts of average conditions beyond the range for which individual daily forecasts have useful skill, but within the span of time during which a dynamical model retains useful information from its initial conditions, as indicated by positive skill of model forecasts of average conditions, currently about two weeks.

moving rapidly eastward, conserving their absolute vorticity. 4) The position of the train of troughs depends upon the zonal index, which is in turn, related to the position of the centers of action. A low zonal index describes a pattern with large excursions of the jetstream to the north and south. A high zonal index describes a less amplified pattern with a strong west-east flow. Surface weather (temperature and total precipitation) were estimated subjectively at first, but statistical downscaling, (Klein et al. 1959), (Klein, 1965) was later used. Physical reasoning methods continued to be used through the 1960s and early-1970s to construct 1-5 day forecasts. By then it had become clear that daily forecasts out to day 5 would eventually be accurate enough that 1-5 day mean forecasts would cease to be required. These were retired in favor of daily forecasts out to day 5 in the mid-1970s.

3. Model-Based Medium Range Forecasts. The success of the 1-5 day forecasts from the 1940s through the 1960s was based firmly upon the Rossby wave theory, as adapted to the practice of prediction by Rossby's very forceful, and creative student, Jerome Namias (Namias, 1956a, b, 1957). This success was in the minds of Vanderman et al. (1976) when they adapted the global, six layer primitive equations model (Shuman and Hovermale, 1968) to their needs (economy) by modifying it to a three layer version (3LPE), to run a set of 18 forecasts out to 10 days during April through July, 1976. The skill of the 11 T and 7 P forecasts from the model which were available for verification, though lower than those made by human volunteers and persistence, were positive (for temperature and near-zero for precipitation. Though modest, these results were encouraging (Vanderman et al. 1976).

In a second experiment, during the winter of 1976-77, 6_10 forecasts were prepared once per week for 15 weeks by humans and the 3LPE (Andrews, 1977). This winter turned out to be an extremely cold winter (Wagner, 1977).   Forecasts for five classes of temperature and three classes of precipitation were prepared.   The skill of these forecasts was low, but consistently positive and the experiment was, again, considered to be a success. During the summer of 1977, a barotropic model extension of the 84-hour Six-Layer Primitive Equation (6LPE) out to 10 days was run and compared with the 3LPE. It proved to be better than the older model (Andrews, 1977). This, coupled with the fact that the skill of the experimental 6-10 day human forecasts, which used the model as a forecast tool, were consistently higher than the model, convinced George Cressman to approve that the implementation of the 6-10 day forecasts into operations, beginning in December, 1977.

 The 6LPE was upgraded to a 7LPE in 1978. The 6-10-day forecast was prepared using mainly this model until August 12, 1980, when the global spectral model (MRF) became operational, replacing the7LPE. The initial configuration was 30 modes and 12 layers to 48 hours at 00Z and to 60 hours at 12Z. At 00Z the run was extended to 144 hours, in a hemispheric version with 24 modes and 12 layers. To get to 252 hours, the 00Z run used the barotropic "mesh" model (November, 1977 through April, 1981). The skill of many forecasts, including 6-10 day T and P forecasts, rose rapidly with the new model (Fig. 3). It is fitting that the GSM, developed by Joe Sela, a former member of the Extended Range Forecast Division, marked the beginning of a long period of gradually improving 6-10 day forecasts.

As more models, and better computers, became available, during the 1980's, it became clear that an average of the models, subjectively weighted by the forecaster in accordance with their expected (or recent) skill, was the most efficient method to incorporate their information. Frank Hughes, among others, did much to develop the use of this "Blend" technique in medium range

forecasting. The 500 mb height forecast which resulted from this poor_man's ensemble of different forecasts then served as the basis for the forecasts of surface parameters. Frank was also responsible for keeping track of the skill of forecasts for each of days 3, 4 and 5 and 6-10 days. His statistics were very useful in demonstrating the progress, or lack of it, being made in these forecast operations. The 80s were also a fertile time for research on low-frequency variability. Simmons et al. (1983) showed how barotropic waves extract energy from the mean flow to create the major teleconnection patterns and centers of action. Attempts were also made (Palmer, 1988, O'Lenic and Livezey, 1989), with varying amounts of success, to improve and understand the predictability of major teleconnection patterns in the ECMWF and MRF models. The frequent changes which were, and are, made in NWP models not only improve them, but also make it difficult to study the behavior of the model over long periods. Hamill et al. (2004) would later illustrate the great value of having a long history (at least 20 years) of model runs.

During the 1990s a number of changes occurred which affected the medium range forecast process.
Workstations became intimately involved, allowing local processing and interaction with databases that mainframes did not. Many previously manual processes, such as plotting and display of maps, was automated and rendered useable through html pages on the internet. The graphical user interface shown in Fig. 4 is one used by the forecaster to create the weighted average of 500 hPa forecasts, the step with which every 6-10 day and 8-14-day forecast begins. Verification became easier to do and its results easier to display. More verification activities were undertaken.

To their great credit, modelers need for ever more powerful computers stayed well ahead of actual computing capability. Improvements to forecasts can be traced to better models, better observational data and better methods of data assimilation (Kalnay et al. 1998). In fact, the increase in skill of operational forecasts also appears to be directly related to computing power (Kalnay et al. 1998). Ensembles made their appearance at NMC on December 7, 1992 (Tracton and Kalnay, 1993), with 14 forecasts all valid at the same time out to 10 days, nearly 30 years after Ed Lorenz made the discovery that some dynamical systems display a sensitive dependence on their initial conditions (Lorenz, 1963), giving birth to chaos theory and a future to ensemble forecasting, which puts this hard fact of life to work to improve the signal-to-noise ratio of the forecast.

The initial reaction among forecasters was to try to look at every one of the ensemble members individually. Eventually, however, skill scores and exhaustion made it clear that the ensemble mean was generally better than any single forecast tool, at least for predicting 500 mb height. Ensemble forecasts from other centers also became available, including those from ECMWF and the Canada Meteorological Center. Strangely, although ensembles improved the use of information from the model, the skill of medium range forecasts leveled out during the 90s (Fig. 3). The relationship of this skill plateau to the predictability of the patterns during that period needs to be examined. It is entirely possible it is due to a period of relatively low predictability.

As computing capability also improved, probabilistic renderings of the ensemble information became available. This led directly to a change to a probabilistic format for 6_10 day forecasts (Fig. 1, 2) and to forecasts for an average of days 8-14 (week 2) in October, 2002.

4. Today's Medium Range Forecast Operation. NCEP's medium range forecasts are now prepared exclusively using output from NWP models. The forecaster first creates a weighted average, or "blend", of the available model forecasts of 500 hPa height, subjectively assigning the weights. An example of a computing tool that permits the forecaster to quickly assemble a weighted mean of available 500 hPa height forecasts is shown in Fig. 4. The resulting map becomes the official 500 hPa forecast and serves as the basis for forecasts of temperature and precipitation. The latter forecasts are informed by a number of techniques which relate conditions at 500 hPa to contemporaneous conditions at the surface. These are called "downscaling methods." Among them is the venerable, but useful, Klein equations. Others include ensemble probabilistic maps of the T and P observed maps that go along with the ten best analogs to the blend map (Fig. 5). Direct model output of precipitation, corrected for recent biases and forecasts from calibrated forecasts (Hamill et al. 2004) is used for precipitation forecasts. Woven throughout the operation, one can still find reminders from the earlier years. For example, until 2002, 5-day means for days 6-10 were the primary medium range forecast. The motion of the long waves is still considered. However, now the question is "which model is moving the long waves properly". Perhaps our greatest challenge is how to assimilate and apply the information from an increasingly large number of forecast tools. The local computing capability of work stations is quite helpful in this regard, as was illustrated in Fig. 4.

Teleconnections and ensembles of the ten best analogs to the 500 hPa forecast now serve as checks on the "sanity" of the model forecasts - if good analogs and strong teleconnections to the predicted pattern were found, it means the model forecast resembles patterns in the historical record of 5-day mean upper-air height patterns. If not, it is more likely that the model pattern is transitory, or simply unlikely to occur and therefore, less likely to be reliable.

Improvements in the use of NWP, and therefore, medium-range forecasts, continue. One of the most exciting is calibration, using decades-long sets of forecasts from an unchanging model, along with observations (Hamill et al. 2004). This method solves the long-existing problem of frequent changes to operational models which, though necessary, make their statistics non-uniform and difficult to use to improve the forecast output. Calibration enhances the information available from ensembles so much that its importance is hard to over_estimate. For example, the jump in the skill of precipitation forecasts (Fig. 3) which begins in 2003 and extends into 2004 coincides with the use of this technique in CPC operational forecasts.

Recent research (Yang and Slingo, 2001, Inness et al. 2003a, b, Woolnough et al. 2000) indicates that improved predictions in middle latitudes may depend on improving the treatment of the tropical oceans, their interactions with the tropical atmosphere and the diurnal cycle of convection. Should improvements such as these lead to better simulation of tropical intra-seasonal oscillations of cloudiness and precipitation, as the research implies, medium range forecasts may very well be usefully extended to weeks 3 and 4 over the next five to 10 years.
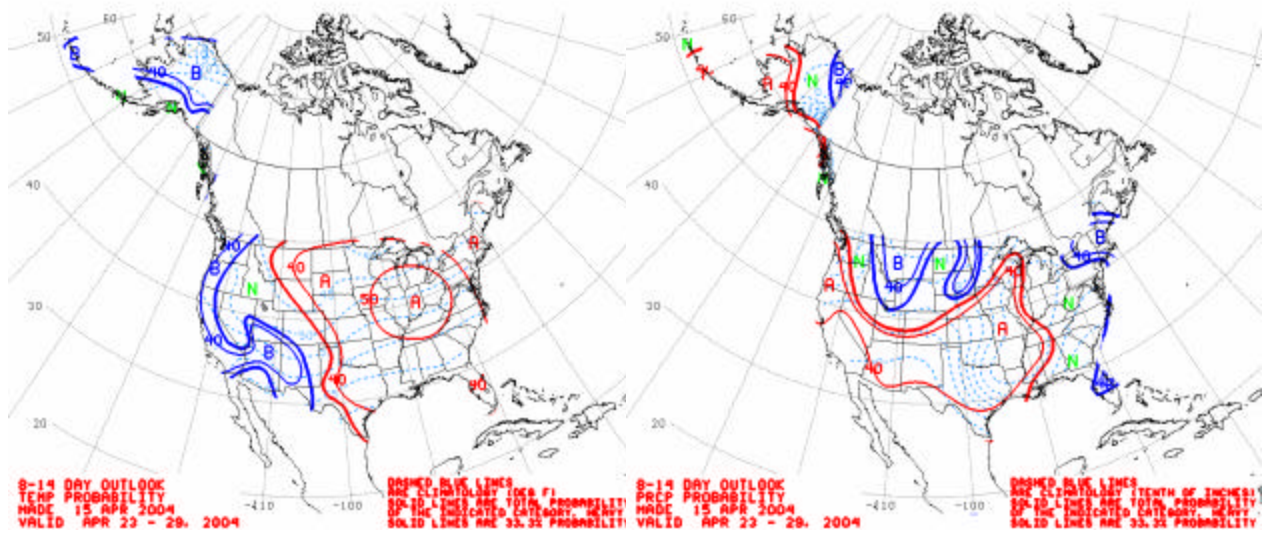
Figure 1. 8-14-day T (top) and P forecasts. Solid contours are the total probability of the indicated category, B stands for below normal, A stands for above normal, N stands for normal.
Heavy solid lines are the 33.3% line. Dashed lines are the normals, in degrees Farenheit, for T and tenths of inches, for P. The categories used are terciles, from the 1971-2000 period.
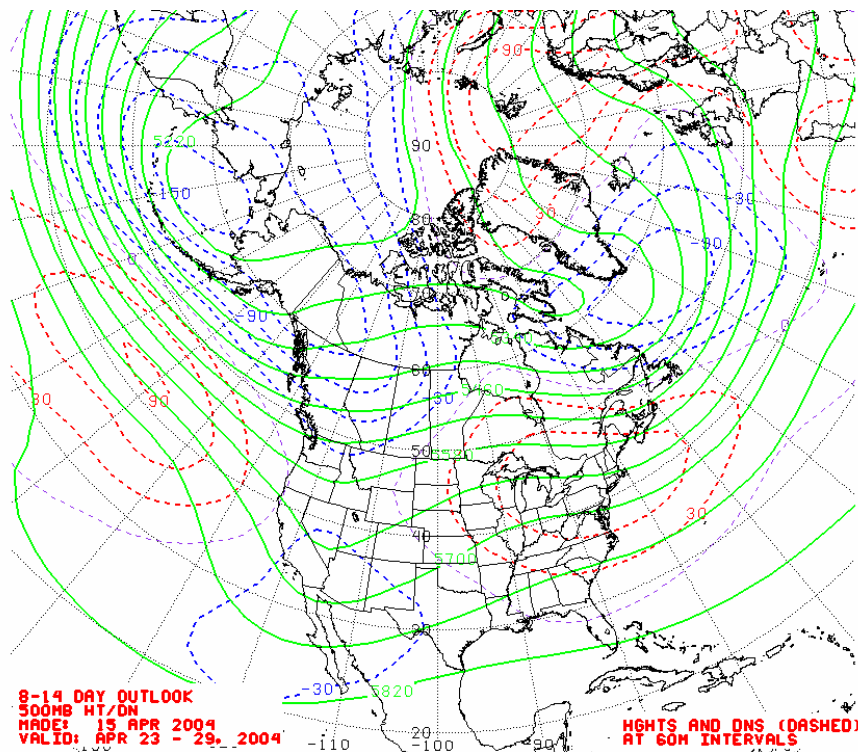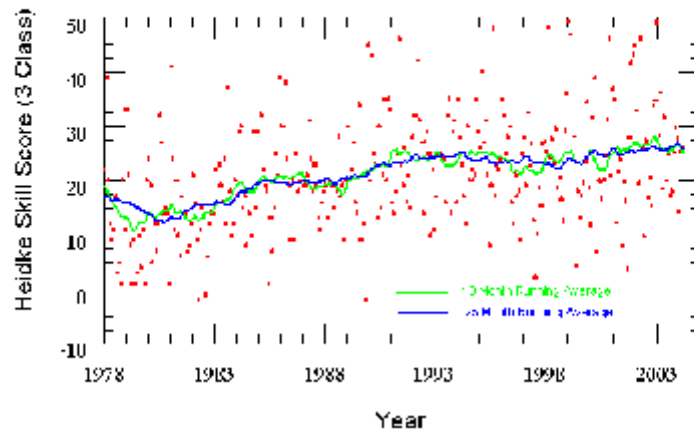

Figure 2. 8-14-day forecast of 500 hPa height (solid lines) and anomalies (dashed lines).

Monthly Average 6 to 10 Day Outlook Heidke Temperature Score

Heidke Skill Score (3 Class)

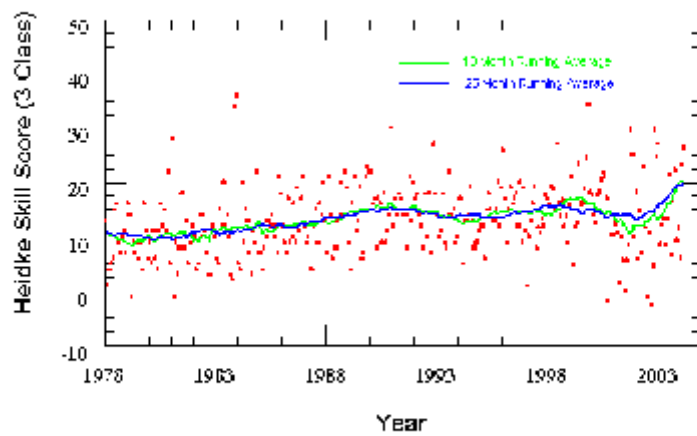## Monthly Average 6 to 10 Day Outlook Heidke Precipitation Score

Heidke Skill Score (3 Class)

Figure 3. Skill, S = ((c-e)/(t-e))*100, of 3-class, 6-10 day forecasts of T (top) and P (bottom). Dots are 1-month average skill. Lines are 13 (green) and 25 (blue) month running means. Random forecasts have zero skill. Perfect forecasts score 100.

Figure 4. Graphical-User-Interface (GUI) to allow forecasters to quickly create a weighted mean 500 hPa height forecast from any of the available models. Though there are not always 120 possible ways to form a weighted mean 500 hPa height forecast map, this GUI makes it possible, in principle. The forecaster selects an averaging period, e.g., D+3, D+4, D+5, ... from either today or yesterday and enters the fractional weight in the text box. The program keeps track of the total weight, which must add to 100.
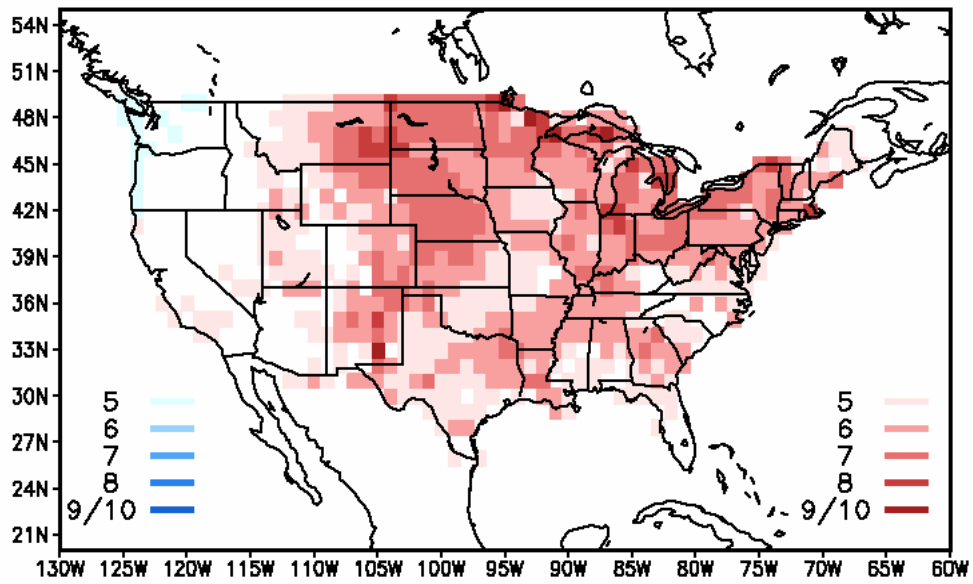
ens Temperature Counts
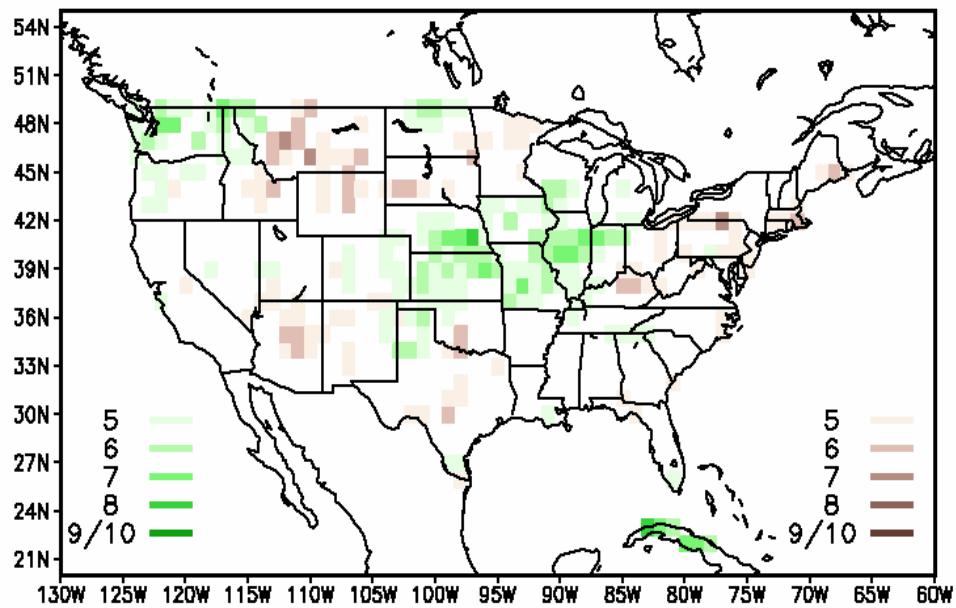
ens Precipitation Counts

Figure 5. Analog ensembles: 8-14-day counts of temperature (top) and precipitation categories from the 10 best analogs to the 500 hPa forecast for April 23-29, made April 15, 2004 (Fig. 2).

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APPENDIX 1: OUTLINE OF THE HISTORY OF PREDICTION.

<Teisserenc de Bort (1883), **centers of action**

<, Abercrombie 1885), Hilebrandsson (1887-1914), Clayton (1936) **weather types**

<Blanford (1884), Lockyer (1904), Braak (1912), Walker (1923, 1924), **statistical prediction methods**

<Baur (1926, 1936), Multanovsky (1933), **weather types, steering**

<Rossby and collaborators (1939), **theory of behavior of centers of action**, based on vorticity redistribution associated with the development and movement of long waves and variations in the zonal westerly index

<Charney, Fjortoft, von Neumann (1950) **1st NWP experiment**, barotropic vorticity equation model

<Lorenz (1963), **chaos, limit of predictability of daily weather of 2 weeks**

<Kalnay, Tracton, 1992, **ensembles.**